SCATTERING OF ULTRASHORT ELECTROMAGNETIC PULSES ON A SYSTEM OF TWO PARALLEL CURRENT SHEETS

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Introduction

This paper summarizes the results of [1], where we gave a theoretical description of the reflection and transmission of a few-cycle laser pulse impinging on two thin metal layers, represented by surface currents. The first description of such a system was given by Sommerfeld [2], where he analyzed the temporal distortion of x-ray pulses impinging perpendicularly on one surface current being in vacuum. This was generalized in [3], in the sense that it allows oblique incidence of the incoming radiation field, and the surface current is embedded in two semi-infinite dielectrics with two different indices of refraction. This system has been investigated from several physical points of view in [5]. Moreover, the relativistic dynamics of the surface current has also been discussed in [4]. The most remarkable feature of this model is that a collective radiation-reaction term derives automatically in the closed system of equations for the surface current. The model described in the present paper is an extension of the one-layer scattering problem to more layers and the analysis is still based on classical electrodynamics and non-relativistic mechanics.

The model description

Consider two parallel metal layers, with thickness much smaller than the skin depth of the radiation field, represented by current sheets, which are embedded in three dielectrics, all with different index of refraction. We study the reflection and transmission of a few-cycle laser pulse impinging on the system of the two thin metal layers. The dynamics of the surface currents and the complete radiation field are described by the coupled system of Maxwell equations and the equation of motion of the electrons which move in two parallel planes.

The main idea of the model construction is to write first Maxwell's equations in all regions and consider the scattering of a p-polarized TM radiation field. The corresponding components of the electric field and magnetic induction in each region can be expressed in terms of the incoming plane wave pulse F, the unknown reflected plane waves f_1, f_3 and the unknown refracted waves g_3, g_5, respectively. We also obtain the boundary conditions for the connecting regions. This means that the jump in the electric field components through the layers is zero and the jump in the magnetic field components induces surface currents in each metal layers. There are two additional equations needed to close the system. These are given by the equation of motion for the surface currents. The resulting coupled system consists of a recurrence relation for f_3 and two delay differential equations for the local displacements δ_{y_2} and δ_{y_4} of the electrons in the metal layers:

$$f_3(t') = \frac{c_5 - c_3}{c_5 + c_3} \cdot \frac{c_1 - c_3}{c_1 + c_3} f_3(t' - 2\Delta t_3) - \frac{2c_5}{c_5 + c_3} \cdot \frac{m}{e} \Gamma_4 \dot{\delta}_{y_4}(t' - \Delta t_3)$$

$$
\begin{aligned}
&+\frac{c_5-c_3}{c_5+c_3}\cdot\frac{2c_1}{c_1+c_3}\left[F(t'-2\Delta t_3)-\frac{m}{e}\Gamma_2\dot{\delta}_{y_2}(t'-2\Delta t_3)\right]\\
\ddot{\delta}_{y_2}(t') &= \frac{2c_1c_3}{c_1+c_3}\left[\frac{e}{m}F(t')-\Gamma_2\dot{\delta}_{y_2}(t')+\frac{e}{m}f_3(t')\right], \qquad (1a)\\
\ddot{\delta}_{y_4}(t') &= \frac{2c_1c_3}{c_1+c_3}\left[\frac{e}{m}F(t'-\Delta t_3)-\Gamma_2\dot{\delta}_{y_2}(t'-\Delta t_3)\right]\\
&+\frac{c_1-c_3}{c_1+c_3}c_3\frac{e}{m}f_3(t'-\Delta t_3)+c_3\frac{e}{m}f_3(t'+\Delta t_3). \qquad (1b)
\end{aligned}
$$

All parameters in the system are given in [1]. Once we know the solution of this system, the reflected wave f_1 and the transmitted wave g_5 can be calculated as

$$
f_1(t') = \frac{1}{c_1+c_3}\left[(c_3-c_1)F(t')-2c_3\frac{m}{e}\Gamma_2\dot{\delta}_{y_2}(t')+2c_3f_3(t')\right], \qquad (2)
$$

$$
\begin{aligned}
g_5(t') &= \frac{2c_1}{c_1+c_3}\left[F(t'+\Delta t_5-\Delta t_3)-\frac{m}{e}\Gamma_2\dot{\delta}_{y_2}(t'+\Delta t_5-\Delta t_3)\right]\\
&+\frac{c_1-c_3}{c_1+c_3}f_3(t'+\Delta t_5-\Delta t_3)-f_3(t'+\Delta t_5+\Delta t_3)-\frac{m}{e}\Gamma_4\dot{\delta}_{y_4}(t'+\Delta t_5). \qquad (3)
\end{aligned}
$$

It is remarkable that the damping terms Γ_2, Γ_4 come automatically in the system, due to the boundary conditions, even without assuming any phenomenological friction.

Compared to the previous studies on the one-layer problem, placing an additional metal layer between dielectrics induces time delays in the system. The sizes of the time delays depend on the distance between the two surface current sheets, the indices of refraction of the dielectrics they are embedded in, and the angle of incidence of the impinging plane wave.

Results and Discussion

In this paper we briefly summarized the results of [1], where we have derived from first principles the coupled system of equations describing the scattering of plane electromagnetic radiation fields on two parallel current sheets, which are embedded in three dielectric media. In this description the radiation field may represent e.g. ultrashort light pulses of arbitrary temporal shape and intensity (within the limit of the non-relativistic description of the local electron motions). This formalism yields a closed coupled set of delayed differential-difference equations for the reflected and transmitted field components and for the electronic velocities in the layers. Based on the Laplace transformation of the unknown time-dependent functions, without any restriction on the physical parameters, we presented exact analytic solutions of this model. We analyzed in details the eigenfrequencies of this dynamical system. The main tool in our analysis is the theory of singularly perturbed systems. We gave several numerical illustrations for the transmission and reflection properties of the two-layer system, and have shown the temporal behavior of the outgoing fields in cases of (few-cycle) ultrashort incident pulses. The sensitivity of the resonant structure of the transmission (and reflection) coefficients against the carrier-envelope phase difference (CEP) of the incoming pulse opens a new way of measuring this CEP phase, thus this result may be of immediate practical importance.

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